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(54) Title: METHODS AND APPARATUS FOR TRANSFER OF HEAT ENERGY BETWEEN A BODY SURFACE AND HEAT TRANSFER FLUID

(57) Abstract: In methods and apparatus for heat exchange to and from a body surface using a heat transfer fluid the fluid is impinged on the surface from a plurality of delivery inlets in the form of a corresponding plurality of spaced delivery streams and is immediately removed from the plenum upon rebounding from the surface through a plurality of spaced removal outlets distributed among the delivery streams, thus establishing corresponding very short uninterrupted flow paths between each inlet and its removal outlet/s. Preferably, the fluid stream velocity is sufficient for it to penetrate and disrupt a fluid boundary layer on the body surface. Each delivery inlet may have its outlet to the surface spaced from 0.001cm to 0.2cm (0.0004in to 0.08in) from that surface. Each delivery inlet may produce a jet impinging the surface of from 0.3cm to 1.5cm (0,12in to 0.6in) diameter. The delivery streams may impinge a flat body surface from a right angle to an acute angle, while when the body surface is curved the delivery streams may impinge from a right angle to one that is tangential thereto. A particular apparatus with which the heat exchanger may be used has a cylindrical rotor rotating within a cylindrical stator so that the body surface is cylindrical; the rotor diameter may be from 0.1cm to 500cm (0.04in to 200ins).

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Methods And Apparatus For Transfer of Heat Energy Between a Body Surface And Heat Transfer Fluid

Technical Field of the Invention

[0001] The invention is concerned with new methods and apparatus for the transfer of heat energy between body surfaces and heat transfer fluids, wherein the surfaces are contacted by the fluids for such transfer. Such apparatus almost universally is referred to as a heat exchanger. More particularly, but not exclusively, the invention is concerned with new methods and apparatus for cooling a surface of a body in which heat energy is being produced, or for heating a surface of a body in which heat energy is being consumed, by contacting the body surface with heat transfer fluid.

Background Art

[0002] The requirement to transfer or exchange heat energy between bodies, and/or between fluids separated by a body wall, and/or between a body and a fluid, is essential in a vast number of processes and apparatus and the design and application of heat exchangers is now a very mature art. Such heat exchange apparatus may consist of a separate structure to which the transfer fluid is supplied and from which it is discharged, or it may be associated with and/or form part of apparatus in which the heat energy is produced or consumed. There is a constant endeavor to make the heat exchange as efficient as possible, and a corresponding endeavor to make the apparatus as compact as possible in order to facilitate minimization of associated parameters, such as the space required, the weight and the cost.

Disclosure of the Invention

[0003] It is the principal object of the invention therefore to provide new methods and apparatus for such transfer of heat energy between body surfaces and heat transfer fluids which facilitate such an endeavor.

[0004] In accordance with the present invention there is provided methods for transferring heat energy to and from a body surface respectively from and to heat transfer fluid that is introduced into and removed from a space bounded by the body surface for heat transfer contact with the body surface, the method comprising:

applying heat transfer fluid introduced into the space to the body surface from a plurality of delivery inlets in the form of a corresponding plurality of spaced delivery streams impinging on the body surface; and

thereafter removing heat transfer fluid rebounding from the surface from the space through a plurality of spaced removal outlets distributed among the delivery streams to establish corresponding flow paths for the heat transfer fluid between each delivery inlet and one or more removal outlets.

[0005] Also in accordance with the invention there is provided new apparatus for transferring heat energy to and from a body surface respectively from and to heat transfer fluid that is introduced into and removed from a space bounded by the body surface for heat transfer contact with the body surface, the apparatus comprising:

a plurality of delivery inlets delivering heat transfer fluid that is introduced into the space to the surface in the form of a corresponding plurality of spaced delivery streams impinging on the body surface;

means for supplying heat transfer fluid to the delivery inlets; and

a plurality of spaced removal outlets distributed among the delivery inlets through which heat transfer fluid rebounding from the surface is removed from the space after its passage in corresponding flow paths established between each delivery inlet and one or more removal outlets.

[0006] Preferably the fluid delivery streams impinge on the body surface at a velocity sufficient to penetrate fully any fluid boundary layer on the body surface.

[0007] Preferably each delivery inlet is disposed immediately adjacent its associated one or more removal outlets to ensure that the corresponding flow path or paths are uninterrupted.

[0008] When the body surface is flat the delivery streams impinge the body surface at an angle thereto from a right angle to an acute angle, and when it is curved about an axis they impinge the body surface at an angle thereto from a right angle to an angle that is tangential to the surface.

[0009] In apparatus in which the body surface is cylindrical it may be of diameter from 0.1cm (0.04in) to 500cm (200ins), and each delivery inlet may be spaced a distance from 0.001cm (0.0004in) to 0.2cm (0.08in) from the surface.

Description of the Drawings

[0010] Particular preferred embodiments of the invention will now be described, by way of example, with reference to the accompanying diagrammatic drawings, wherein:-

[0011] Figure 1 is a part elevation, part longitudinal cross section, through a first embodiment of heat transfer apparatus of the invention as applied to a specific form of material processing apparatus, and illustrating a corresponding method of heat energy transfer of the invention;

[0012] Figure 2 is a longitudinal cross section through a part of the apparatus of the apparatus of Figure 1 to a larger scale to show in greater detail the structure of the heat exchange apparatus;

[0013] Figure 3 is a transverse cross section through apparatus as shown in Figures 1 and 2, taken on the line 3-3 in Figure 1, to show the cylindrical members and their axial relation to one another;

[0014] Figure 4 is a cross section similar to Figure 2 in which the streams of heat transfer fluid impinging the surface to be cooled or heated, as seen in transverse cross section, are directed at the surface at an angle other than perpendicular (at a right angle) thereto;

[0015] Figure 5 is a cross section similar to Figure 3 in which the streams of heat transfer fluid impinging the surface to be cooled or heated, as seen in longitudinal cross section, are directed at the surface at an angle other than perpendicular (at a right angle) thereto; and

[0016] Figures 6 and 7 are longitudinal cross sections through apparatus that are other and further embodiments of the invention.

Modes for Carrying out the Invention and Industrial Applicability

[0017] Similar or equivalent parts are given the same reference number in all of the figures of the drawings, wherever that is possible. The thickness of various walls and the spacing between certain surfaces are exaggerated whenever necessary for clarity of illustration.

[0018] A particular apparatus for high shear processing consists of two cylinders mounted one inside the other for rotation relative to one another about a common axis, the cylinders providing an annular processing gap between their opposed inner

and outer surfaces. The materials to be processed are fed into the annular space which is of specific, very small dimensions in which the processing that is taking place is independent of Avolume@ effects, being constituted instead by the interaction of boundary layers of the materials on the opposed surfaces, with or without an intervening layer that, if present, is too thin for so-called Taylor vortices (see below) to be established. Immediately upon entry of the material or materials into the annular space a very large interfacial contact area is produced which is subject to extreme rates of surface renewal. Unusually high shear rates of very uniform value can be created which, due to the confinement of the material/s in a narrow gap of precise predetermined dimensions, results in the creation of vortices of correspondingly small dimension which drastically enhance mass, heat and momentum transfer. The inherent generation in liquid bodies of very small eddies of minimum size of about 10-20 microns diameter by conventional bulk volume stirring processes was first shown by Dr. A. N. Kolmogoroff, after whom such eddies are named. The eddies that are produced in this apparatus are much smaller than Kolmogoroff vortices and are therefore referred to as "sub-Kolmogoroff" vortices, while eddies that are much larger than Kolmogoroff vortices are referred to as "supra-Kolmogoroff" vortices. Such apparatus is described and shown, for example, in my US Patents Nos. 5,279,463 (issued 18 January, 1994) and 5,538,191 (issued 23 July 1996), and in my US application Serial No. 09/802,037, filed March 7, 2001, the disclosures of which are incorporated herein by this reference. In another type of the apparatus described in these disclosures the - cylindrical rotor and stator have their longitudinal axes parallel but displaced from one another to provide an annular flow passage that varies in radial dimension about the circumferences of the opposed surfaces. The passage thus comprises a flow path containing a zone in which the passage radial spacing is smaller than in the remainder of the passage to provide a highest-shear processing zone in which free supra-Kolmogoroff eddies are suppressed.

[0019] Processing apparatus as briefly described above takes advantage of the special properties of the thin tenacious boundary layer that is always present whenever a viscous fluid is in contact with a surface, together with the interaction that can be produced between two boundary layers on two relatively moving surfaces when they are sufficiently close together to interact. The most practical

form taken by the apparatus is two coaxial cylinders with an annular processing space between them, the inner cylinder being rotated while the outer one is stationary. The type of flow obtained between two such surfaces when they are relatively widely spaced is commonly known as Couette flow and has been well described by G.I. Taylor who showed that when a certain Reynolds number was exceeded the previously stratified flow in the annular space became unstable and vortices appeared, now known as Taylor vortices, whose axes are located along the circumference of the rotor parallel to its axis of rotation and which rotate in alternately opposite directions. The conditions for the flow to become unstable in this manner can be expressed with the aid of a characteristic number now known as the Taylor number, depending upon the radial width of the annular gap, the radius of the rotor, and its peripheral velocity. As is described in more detail in my prior application Serial No. 09/802,037 filed March 7, 2001 referred to above, when using such apparatus for thorough and uniform high-shear micro-mixing the presence of the Taylor vortices inhibits the action or reaction desired, since the material to be treated becomes entrained in the vortices and consequently at least partially segregated, whereupon high-shear mixing becomes impossible and instead much slower molecular diffusion processes predominate. The spacing between the external rotor surface and the internal stator surface must therefore be small enough that Taylor vortices are not generated.

[0020] Such methods and apparatus are operable, for example, to quickly forcibly dissolve gases in liquids in which they are normally of low solubility , or to virtually instantaneously emulsify non-miscible liquids, or to chemically react two or more materials together with very high reaction rates, sometimes even in the absence of the catalysts, special solvents, surface active materials, etc. that frequently are required in conventional processes to obtain economically acceptable reaction rates.

In general, most chemical reactions and many physical reactions are to a greater or lesser degree either endothermic or exothermic, and many are quite strongly so. The higher reaction rates that are possible result in a corresponding considerably increased production or loss of heat, some of which can be transferred out of the apparatus via the exiting fluid/s, but the remainder of which must be transferred though the walls of the stator and/or rotor if the process temperature is to be maintained within required limits. Another factor that is important in such apparatus

is that the heat conductivity of the two thin boundary layer films is very high, since there is no bulk layer between them through which the heat must pass, as with conventional bulk stirring systems. The achievement of the highest possible heat transfer rate, if possible higher than is strictly necessary in order to provide a margin for adjustment, is therefore desirable to ensure that the processing temperature can at all times readily be maintained within those required limits, which can constitute a very narrow range, e.g. ±1°C.

[0021] In apparatus as illustrated schematically by Figure 1, first and second reactant materials are fed from respective supply tanks 10 and 12 via respective metering pumps or valves 14 and 16 to an inlet 18 at one end of the apparatus. If required optional functional materials such as catalysts, reactant gas/es, surfactant/s, etc. as required for the process, are fed from a third supply tank 20 also via a metering pump or valve 21. With the high reaction rates that are obtainable it is preferred to feed the materials into the processing zone as accurately as possible in the stoichiometric ratio required for any reaction that takes place. Separate inlets 14 can of course be used and, if used, will be distributed around the circumference of the apparatus and/or spaced longitudinally along the flow path through the apparatus.

[0022] An apparatus baseplate 22 carries rotor bearing supports 24, stator supports 26 and a variable speed electric drive motor 28. A cylindrical tube 30 of uniform diameter and wall thickness along its length constitutes the apparatus stator body and is mounted on the supports 26, the tube being enclosed by another cylindrical tube 32 that is coaxial therewith and extends along substantially its entire length, this tube 32 constituting the outermost casing of a heat exchanger of the invention. Both of these tubes have longitudinal axes that are coincident with one another and lie on the common central longitudinal line 33. A rotor shaft 34 is carried by the rotor bearing supports 24 with one end connected to the motor 28. The shaft carries a cylindrical rotor 36, the longitudinal axes of rotation of both the shaft and the rotor body being coincident with one another along the line 33, and therefore coincident with the longitudinal axis of the stator tube 30. An annular cross section processing passage or chamber 38 of uniform radial dimension around its circumference, and with a longitudinal axis coincident with the other axes is formed between inner cylindrical surface 40 of stator 30, outer cylindrical surface 42 of rotor

36, and inner annular surfaces 44 of two end closure members 46, the ends of the chamber being closed against leakage by respective end seals 48 that surround the shaft 34. Material that has been processed in the chamber 38 is discharged through an outlet 50 at the other end.

[0023] As has been stated above, in practice it is unusual for a physical and/or chemical reaction to proceed isothermally, i.e. without the generation or consumption of heat energy, with the result that the material being processed, as well as the cylindrical wall surfaces 40 and 42 must be cooled or heated. It is also usual that for optimum efficiency in carrying out the process the temperature of the material while being processed must be maintained in a range between certain limits, which can be quite narrow and also quite critical and may be correspondingly difficult to achieve. The heat exchange means provided must therefore provide adequate heat exchange capacity if a temperature within the required range is to be maintained. A common prior art solution is to surround the stator with a cylindrical casing through which heat exchange fluid, usually a liquid, and if possible water, is passed, the heat exchange fluid flowing along outer surface 52 of the stator wall.

[0024] The material flowing in the processing passage 38 forms a respective boundary layer on each of the cylindrical surfaces 40 and 42, the thicknesses of which are determined primarily by the material viscosity and its relative flow velocity over the surfaces in the flow path, which in this apparatus may be taken as one circumferential flow length around the stator surface 40 or the rotor surface 42, which are approximately equal. The difference between the internal diameter of the stator surface 40 and the external diameter of the rotor surface 42 is such that the radial dimension of the processing passage 38 is at most just equal to the combined thicknesses of the two boundary layers back-to-back, so that there is no room between them for an intervening bulk layer of radial dimension sufficient to permit Taylor vortices to be formed and disrupt the high-shear mixing that takes place. As a specific example, with apparatus in which the rotor circumference was 40cm (16in), the rotor rotated at 2,000 revolutions per minute, and the kinematic viscosity was 0.000001 m^2/sec, the thickness of a single laminar boundary layer was 0.85mm (0.033in), and therefore that of back to back interacting layers 1.7mm (0.067in). The "molecular" size eddies that are induced by this interaction of the two layers give rise to physical interactions and/or chemical reactions of the material in the

passage 38 that are area based rather than volume based as with prior art processes, so that, for example, immiscible materials rapidly interact to give homogeneous emulsions, gas entrainment is immediate, and chemical and biological reactions now proceed much more rapidly. It may be noted however that, although the invention is described as used in conjunction with this very specific form of processing apparatus, it has general application in the entire field of heat exchange, as will be apparent from the description that follows.

[0025] The heat to be removed or added passes through the stator body wall 30, which is therefore as highly heat transmissive as possible, as by being made of highly heat conductive material, and being as thin as possible consistent with the required structural strength. In this particular embodiment a heat exchange or transfer structure comprises an inner cylindrical tubular member 54 and an outer cylindrical tubular member 56 which are coaxial with one another, and also with the stator 30, the outermost casing 32 and the rotor 36. The two cylindrical members 32 and 56 form between them an annular heat transfer fluid receiving plenum 58, the fluid entering the plenum via one or more inlets 60. The two cylindrical members 54 and 56 form between them an annular heat transfer fluid discharge plenum 62, the fluid leaving the plenum via a one or more outlets 64. The cylindrical member 54 and the outer cylindrical surface 52 of the stator form between them an annular heat exchange or heat transfer plenum 66, in which the transfer of heat energy between the surface 52 and the heat exchange fluid takes place.

[0026] As is usual in heat exchange apparatus the inlet or inlets 60 are placed at one end, while the outlet or outlets are placed at the other end to establish a flow path for the heat transfer fluid along its entire length. It is also usual to arrange that the direction of flow of the fluid is opposite to that of the material, although concurrent flow is also possible. It is inevitable that a temperature difference will occur between the entering fluid and that discharging at the outlet/s, and this difference must of course be maintained within a limit set for the particular process, so that the temperature of the material while it is being processed is also maintained within the predetermined limit values. There are in practice a number of ways in which the required limits can be achieved, as by increasing the size of the heat exchanger and/or increasing the rate at which the heat transfer fluid is pumped through it. In this embodiment another way is illustrated, namely by dividing the apparatus into a

plurality of shorter units (six in this embodiment) that are closely spaced in succession along the length of the stator, each with its own inlet/s 60 and outlet/s 64, and supplied with the heat transfer fluid in parallel with one another, usually from a common source (not shown). The length of each unit, and consequently the number required, is determined principally from consideration of the temperature differences that are to be maintained in both the transfer fluid and the material, and the volume and pumping pressure required for the transfer fluid.

[0027] The heat transfer fluid is delivered from the receiving plenum 58 to the heat transfer plenum 66 via a large number of closely uniformly spaced, radially inward directed passages 68. Each passage is formed by a respective tube 70 that extends from the cylindrical member 56 and opens at its radially outer end at an inlet port 72 to the receiving plenum 58; the tube passes through a hole in the cylindrical member 54, the junction being sealed to prevent leakage between the plenums. The tube terminates very close to the stator outer surface 52 at an outlet port 74, which also constitutes a corresponding delivery inlet port (also employing the reference 74) to the transfer plenum 66. Each passage 68 delivers its portion of the transfer fluid to the surface 52 in the form of a radially inward directed delivery jet stream that impinges forcibly on the surface 52, preferably at a velocity that is sufficient for it to penetrate and completely disrupt the barrier layer of the fluid thereon. The heated or cooled transfer fluid rebounding from the surface is promptly, almost immediately, removed from the heat transfer plenum 66 via an approximately equally large number of spaced removal outlets 76, of at least the same total flow capacity, formed in the cylindrical member 54, through which the fluid passes into the fluid removal plenum 62 and out through exit or exits 64. The inlets 74 and outlets 76 are interspersed and disposed relative to one another such that each inlet 74 is surrounded by a number of immediately adjacent outlets 76, and vice versa, thereby providing flow paths for the fluid after it has impinged on the surface 52 and rebounded therefrom that are uninterrupted and are as short as possible so as to achieve the required prompt removal. The transfer fluid passing out of the heat exchanger may be discarded, but more usually will be passed to an external heat exchanger (not shown) in which heat energy is removed or added, as is required with careful control of the exit temperature of the heat transfer fluid, so that it can be recycled back to the processing apparatus.

[0028] An inherent characteristic of the methods and apparatus of the invention is that the heat transfer fluid engages the surface involved in the heat transfer for a relatively very brief period of time, as contrasted with most conventional apparatus in which contact is prolonged for as long as possible, and is then immediately removed and delivered into a plenum 62 spaced from the surface. It is a preferred characteristic that the contact which does take place is extremely forceful and intimate, directly with the surface without the intervention of the usual fluid barrier layer, so that there is enhanced opportunity for heat transfer despite the very short contact engagement time. It is a consequence of this very short contact period that the majority of the temperature difference in the heat transfer fluid between the inlet/s 60 and the outlet/s 64 takes place during this period, with relatively little of the difference produced before the surface 52 is engaged by the fluid, and after the fluid has left the heat exchanger plenum 66 and exited through the outlet/s, giving the possibility of much more precise control of the value of the temperature difference than is possible when the contact time with the heat exchange surface is substantial. A corollary to this is that the wall of the cylindrical member 56 containing the inlet ports 72 should be of low heat transmission capability to minimize heat transfer between the incoming and outgoing flows of heat transfer fluid. This can be achieved, for example, by making it thicker, bearing in mind that the size, weight, cost, etc. are thereby increased, or even by making it of a heat insulating material, such as plastics or ceramic.

[0029] As examples of specific dimensions for the methods and apparatus of the invention, in apparatus of the kind specifically described herein, each outlet (delivery) port 74 to the heat exchange plenum directing the respective stream of fluid against the surface 52 may be spaced a distance of from 0.001cm to 0.2cm (0.0004in to 0.08in) from that surface. The diameter of the rotor and stator body surfaces of an individual machine can vary widely. For example, the rotor body can be of diameter as small as about 0.1cm (0.04in), having the form of a solid needle rotating within a stator tube of the required dimensions. Such an embodiment will usually comprise a single unit in a large array thereof, e.g. as many as one thousand at a time, such an array being used to perform a corresponding number of simultaneous chemical and/or pharmaceutical reactions in what is now known as

combinatorial chemistry, the reactions usually differing from one another by only minor increments. A practical upper limit for the rotor diameter is about 500cm (200in), and is set primarily by the engineering design requirements to maintain the radial dimension of the processing passage 38 sufficiently constant with a rotor of this diameter, which will also usually be of substantial length in order to give a desired high material throughput.

[0030]The dimensions of the delivery ports 74 into the respective heat exchange plenum will also depend upon the rotor diameter, the rate of heat exchange required, the degree of temperature control needed, and therefore the rate of flow of the heat exchange fluid to ensure that the boundary layer is penetrated. As a specific example, with a rotor of diameter of about 8cm (3.2in) each delivery nozzle will provide a delivery port 74 of between 0.3cm and 1.5cm (0.12in and 0.6in). The fluid removal outlets 76 must together provide an exit flow rate at least equal to the inlet flow rate of the delivery inlet 74, and preferably somewhat greater, the number, size and distribution of the outlets 76 being chosen to obtain the desired objective of prompt removal from the plenum 66 with the shortest possible uninterrupted flow path. The rate at which the heat exchange fluid is passed in the flow paths will be such that its impact velocity against the stator surface 52 disrupts the barrier layer thereon, attainment of this objective being indicated by a corresponding increase in the rate of heat transfer obtained.

[0031]In the embodiment described so far the fluid streams are directed radially inward toward the common axis line 33 and hence impinge on the stator outer surface at a right angle, as viewed both transversely and longitudinally. In other embodiments in which the stator is a cylinder, or otherwise curved, this angle is not a right angle and is instead between a right angle and an angle that is tangential to the surface. Such an embodiment is illustrated, for example, by Figure 4, which is a transverse cross section through an apparatus as otherwise shown in Figures 1-3, but wherein the tubes 70 providing the passages 68 are correspondingly inclined. With such an inclination the fluid streams not only disrupt the boundary layers by their impact thereon, but also have a component tending to shear the layers away from their associated surfaces, with the possibility that lower velocities can be employed that are still effective to produce intimate engagement of the impacting streams with the surface 42. Figure 5 illustrates an embodiment in which the tubes

70 and the corresponding jets of heat transfer fluid are delivered to the surface 42 in the longitudinal direction at an angle that is other than a right angle, the Figure being a longitudinal cross section through apparatus as otherwise shown in Figures 1-3. The Figure also illustrates the situation when the surface 42 is flat (see also Figures 6 and 7), wherein the delivery streams impinge the surface 42 at an angle from a right angle to an acute angle whose minimum value is set by the physical constraints imposed by the size of the tubes 70 and the structure required to support them in the apparatus.

[0032] Figures 6 and 7 show the application of the invention to heat exchange apparatus not necessarily physically associated with, or part of, any specific other apparatus. The heat exchange apparatus of Figure 6 comprises a heat exchange structure (subscripts A) on one side of a flat plate 30 that heats or cools the plate, while a second structure (subscripts B) has its heat exchange fluid heated or cooled by its contact with the plate 30. Thus, the same references that are used in the preceding Figures are used herein with the suffix A or b respectively for the same elements associated with the two different structures. The plate 30 has respective inner surfaces 40A and 40B and is equivalent to the stator outer casing 30 of the apparatus of Figures 1-5. The heat exchange apparatus overall takes the form of a rectangular structure that has the plate 30 forming one wall of the two structures, being attached to the remainder of each structure with a respective gasket 78 between them. Inner and outer flat plates 54 and 56 are equivalent to the cylindrical members 54 and 56 respectively of the apparatus of Figures 1-5, the plates having tubes 70 mounted in holes therein that provide respective passages 68 conveying the heat transfer fluid from plenum 58 via inlet ports 72 and outlet ports 74 to the heat exchange plenum 66. Fluid rebounding from the inner plate surfaces 40A and 40B is immediately discharged through the respective outlet ports 76A and 76b to the respective fluid discharging plenum 66A and 66B, and thence to the respective outlets 64A and 64B. Figure 7 shows a heat exchanger whose function is to heat or cool the plate 30.

List of Refer nce Signs for Drawings

10 Supply tank for first reactant
12 Supply tank for second reactant
14 Metering pump for first reactant
16 Metering pump for second reactant
18 Inlet to processing chamber
20 Supply tank for further reactant/s
21 Metering pump for further reactant/s
22 Apparatus baseplate
24 Rotor bearing supports
26 Stator supports
28 Variable speed electric drive motor
30 Cylindrical stator body
32, 32A, 32B Heat exchanger outermost casing/s
33 Common line for various longitudinal axes
34 Rotor drive shaft
36 Cylindrical rotor body
38 Annular processing passage or chamber
40, 40A, 40B Stator inner cylindrical surface/s
42 Rotor outer cylindrical surface
44 End member annular surfaces
46 End closure members
48 End seals
50 Processing passage outlet
52 Stator outer cylindrical surface
54, 54A, 54B Heat exchanger inner member/s
56, 56A, 56B Heat exchanger outer tubular member/s
58, 58A, 58B Heat exchange fluid receiving plenum/s
60, 60A, 60B Inlet to plenum 58, 58A, 58B respectively
62, 62A, 62B Heat exchange fluid discharging plenum/s
64, 64A, 64B Outlet from plenum 62, 62A, 62B respectively
66, 66A, 66B Heat exchange plenum/s

68, 68A, 68B Passages from plenums 58, 58A, 58B respectively to plenums 66, 66A, 66B respectively

70, 70A, 70B Tubes forming passages 68, 68A, 68B respectively

72, 72A, 72B Inlet ports of tubes 70, 70A, 70B respectively from plenums 58, 58A, 58B respectively

74, 74A, 74B Outlet ports of tubes 70, 70A, 70B respectively and delivery inlets to plenums 66, 66A, 66B respectively

76, 76A, 76B Fluid removal outlets from plenums 66, 66A, 66B respectively to plenums 62, 62A, 62B respectively

78 Gasket between body 30 and heat exchange structure

I CLAIM:

1. A method for transferring heat energy to and from a body surface respectively from and to a heat transfer fluid within a space bounded by the body surface for heat transfer contact with the body surface, the method comprising:

applying heat transfer fluid to the space and to the body surface from a plurality of delivery inlets in the form of a corresponding plurality of spaced delivery streams impinging on the body surface; and

thereafter removing heat transfer fluid rebounding from the surface from the space through a plurality of spaced removal outlets distributed among the delivery streams to establish corresponding flow paths for the heat transfer fluid between each delivery inlet and one or more removal outlets.

2. A method as claimed in claim 1, wherein the heat transfer fluid delivery streams impinge on the body surface at a velocity sufficient to penetrate and thereby disrupt a boundary layer formed by any fluid on the body surface.

3. A method as claimed in claim 1, wherein each delivery inlet is a delivery port from which a respective stream of fluid impinges on the body surface and the delivery port is spaced a distance of from 0.001cm to 0.2cm (0.0004in to 0.08in) from the body surface.

4. A method as claimed in claim 1, wherein each delivery inlet is disposed immediately adjacent its associated one or more removal outlets to ensure that the corresponding flow path or paths between the delivery inlet and its corresponding outlet or outlets are uninterrupted.

5. A method as claimed in claim 1, wherein each delivery inlet is disposed immediately adjacent its associated one or more removal outlets to ensure that the heat transfer fluid impinging on the body surface is removed promptly and by flow paths between each delivery inlet and its corresponding outlet or outlets that are uninterrupted and as short as possible.

6. A method as claimed in claim 1, wherein the delivery streams impinge the body surface at an angle from a right angle to an acute angle thereto.

7. A method as claimed in claim 1, wherein the body surface is flat and the delivery streams impinge the body surface at an angle from a right angle to an acute angle thereto.

8. A method as claimed in claim 1, wherein the body surface is curved about an axis and the delivery streams impinge the body surface at an angle from a right angle to an angle that is tangential thereto.

9. Apparatus for transferring heat energy to and from a body surface respectively from and to a heat transfer fluid within a space bounded by the body surface for heat transfer contact with the body surface, the apparatus comprising:

a plurality of delivery inlets delivering heat transfer fluid to the space and to the surface in the form of a corresponding plurality of spaced delivery streams impinging on the body surface;

means for supplying heat transfer fluid to the delivery inlets for discharge therefrom as respective delivery streams; and

a plurality of spaced removal outlets distributed among the delivery inlets removing heat transfer fluid rebounding from the surface from the space via corresponding flow paths for the heat transfer fluid established between each delivery inlet and one or more removal outlets.

10. Apparatus as claimed in claim 9, wherein the means for supplying heat transfer fluid to the delivery inlets supply the heat transfer fluid in quantity such that the resultant delivery streams impinge on the body surface at a velocity sufficient to penetrate and thereby disrupt a boundary layer formed by any fluid on the body surface.

11. Apparatus as claimed in claim 9, wherein each delivery inlet is a delivery port from which a respective stream of fluid impinges on the body surface and the delivery port is spaced a distance of from 0.001cm to 0.2cm (0.0004in to 0.08in) from the body surface.

12. Apparatus as claimed in claim 9, wherein each delivery inlet is disposed immediately adjacent its associated one or more removal outlets to ensure that the corresponding flow path or paths between the delivery inlet and its corresponding outlet or outlets are uninterrupted.

13. Apparatus as claimed in claim 9, wherein each delivery inlet is disposed immediately adjacent its associated one or more removal outlets to ensure that the heat transfer fluid impinging on the body surface is removed promptly and by flow paths between each delivery inlet and its corresponding outlet or outlets that are uninterrupted and as short as possible.

14. Apparatus as claimed in claim 9, wherein the delivery streams of fluid impinge the body surface at an angle from a right angle to an acute angle thereto.

15. Apparatus as claimed in claim 9, wherein the body surface is flat and the delivery streams of fluid impinge the body surface at an angle from a right angle to an acute angle thereto.

16. Apparatus as claimed in claim 9, wherein the body surface is curved and the delivery streams of fluid impinge the body surface at an angle from a right angle to an angle that is tangential thereto.

17. Apparatus as claimed in claim 9, wherein each delivery inlet is a delivery nozzle discharging a stream of fluid of diameter at the nozzle exit from 0.3cm to 1.5cm (0.12in to 0.6in).

18. Apparatus as claimed in claim 9, wherein the body surface has an inner surface extending parallel thereto to provide a heat exchange plenum between them;

wherein the inner surface has an outer surface extending parallel to it to provide a heat exchange fluid discharging plenum between them;

wherein the outer surface has an outermost casing surface extending parallel to it to provide a heat exchange fluid receiving plenum between them; and

wherein means for delivering heat exchange fluid from the heat exchange fluid receiving plenum to the heat exchange plenum comprises a plurality of tubes each opening at one end to the heat exchange fluid receiving plenum and at its other end close to the body surface.

19. Apparatus as claimed in claim 9, wherein the body surface is cylindrical and has an inner cylindrical surface extending parallel thereto to provide an annular transverse cross section heat exchange plenum between them;

wherein the inner cylindrical surface has an outer cylindrical surface extending parallel to it to provide an annular transverse cross section heat exchange fluid discharging plenum between them;

wherein the outer cylindrical surface has an outermost cylindrical casing surface extending parallel to it to provide an annular transverse cross section heat exchange fluid receiving plenum between them; and

wherein means for delivering heat exchange fluid from the heat exchange fluid receiving plenum to the heat exchange plenum comprises a plurality of tubes each opening at one end to the heat exchange fluid receiving plenum and at its other end close to the body surface.

20. Apparatus as claimed in claim 9, wherein the body surface is cylindrical and each delivery inlet is a delivery nozzle discharging a stream of fluid of diameter at the nozzle exit from 0.3cm to 1.5cm (0.12in to 0.6in).

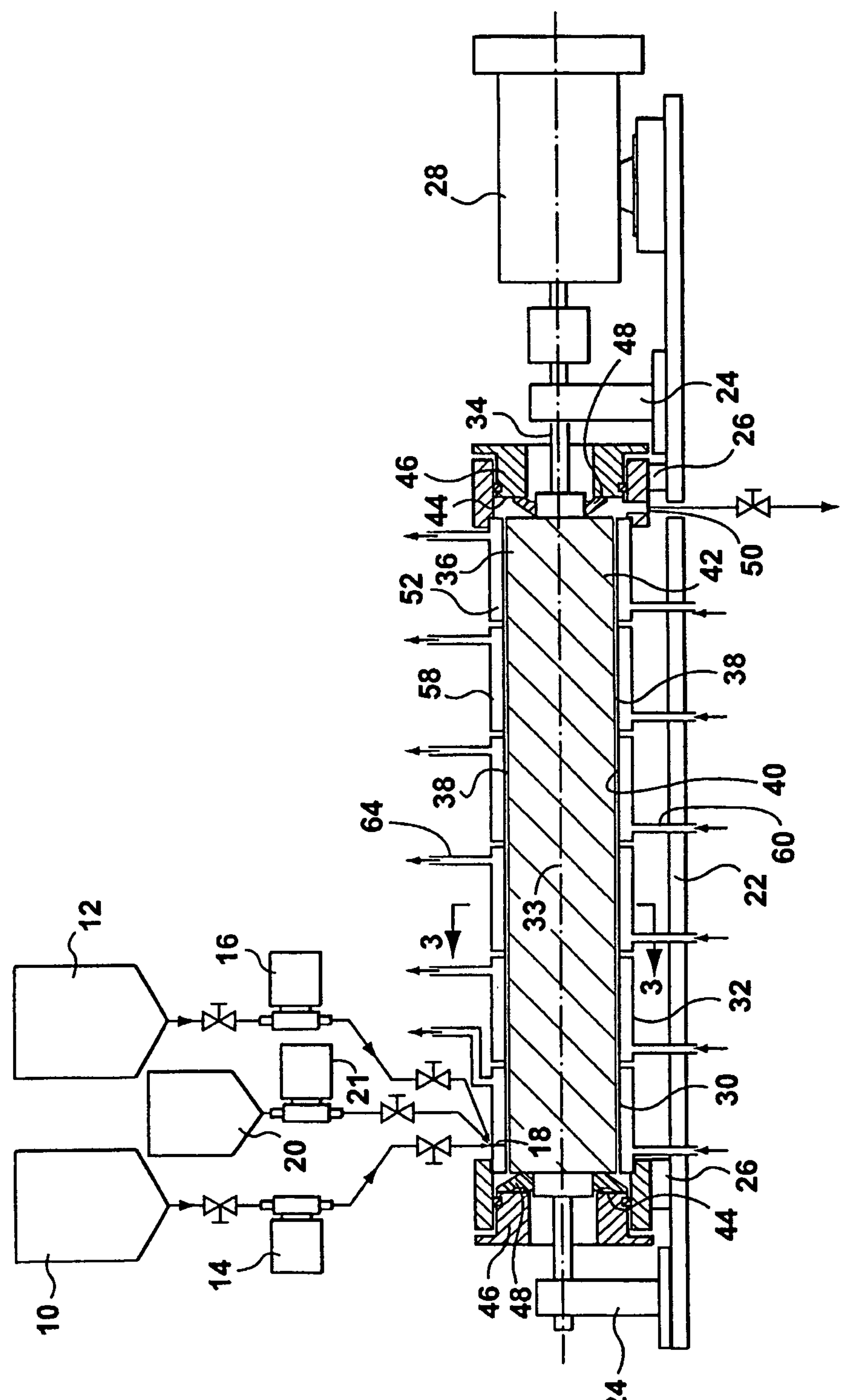
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FIG. 1

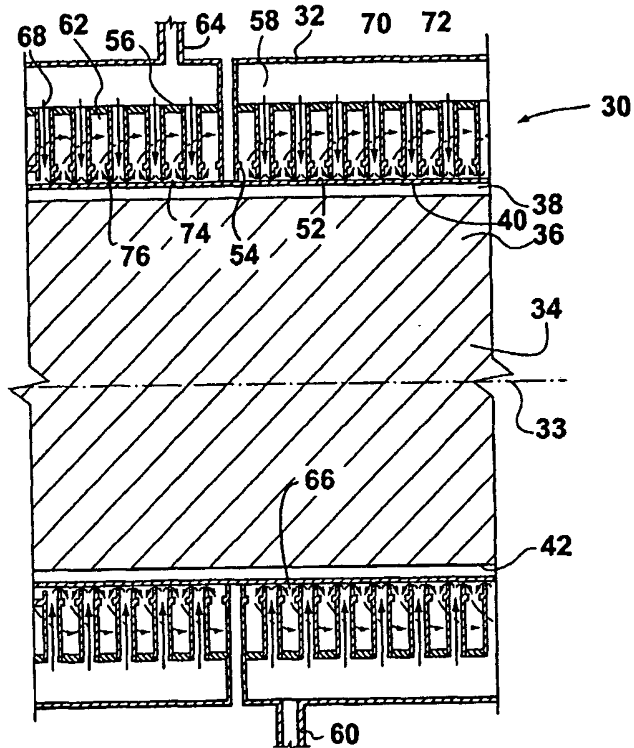
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FIG. 2

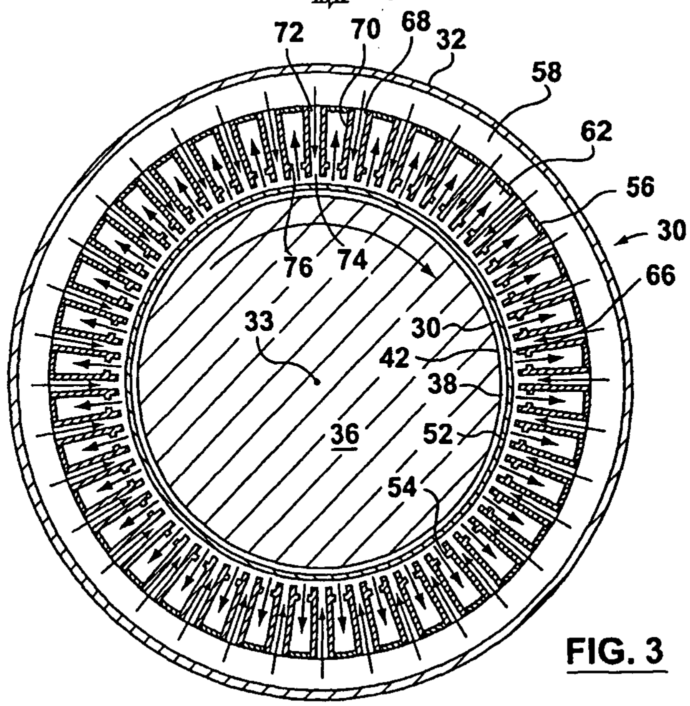
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FIG. 3

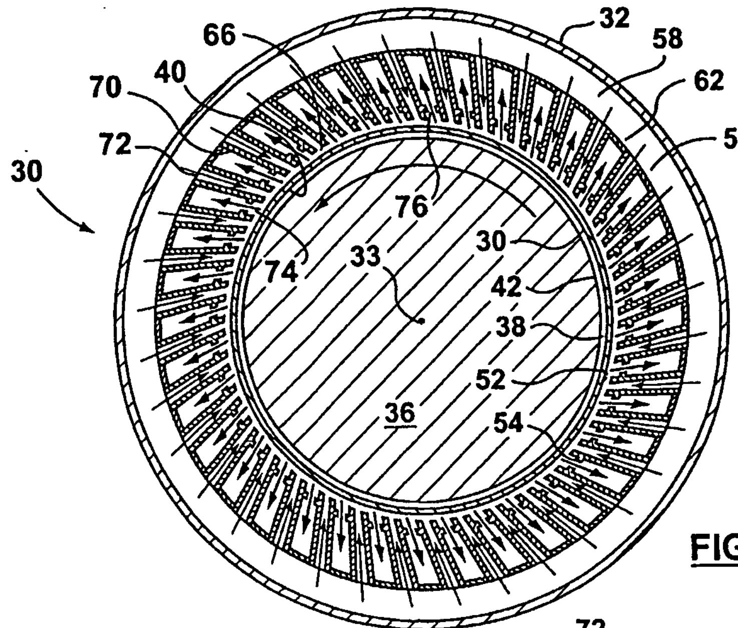
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FIG. 4

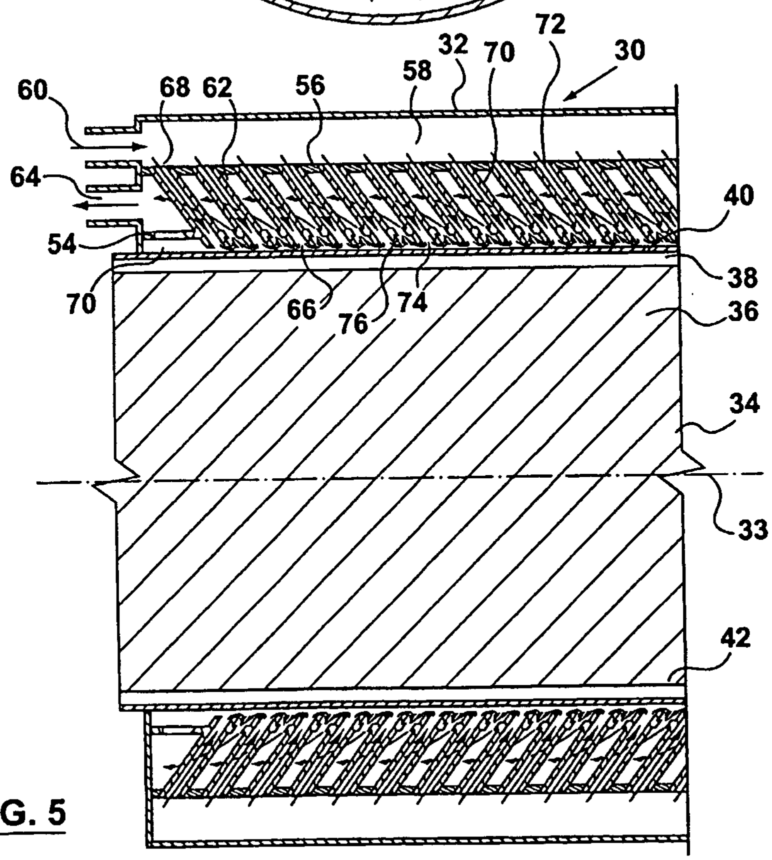
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FIG. 5

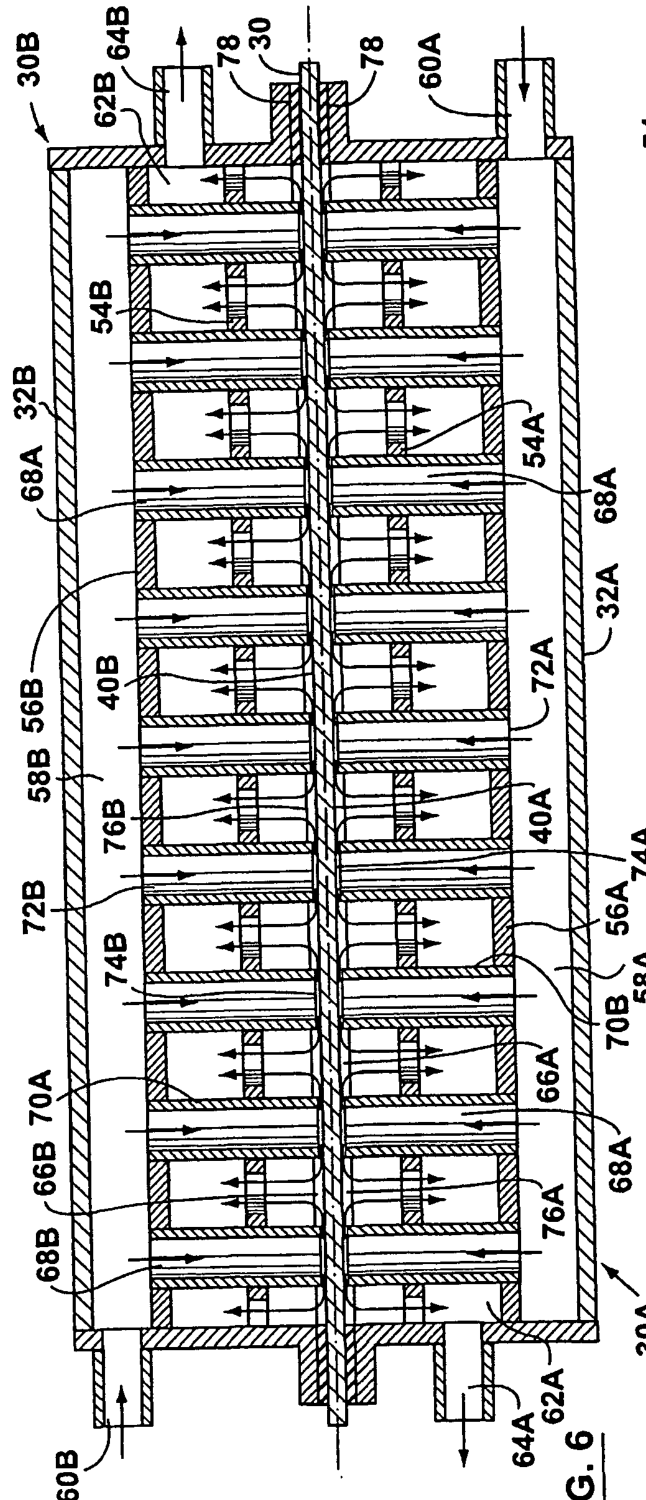
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FIG. 6

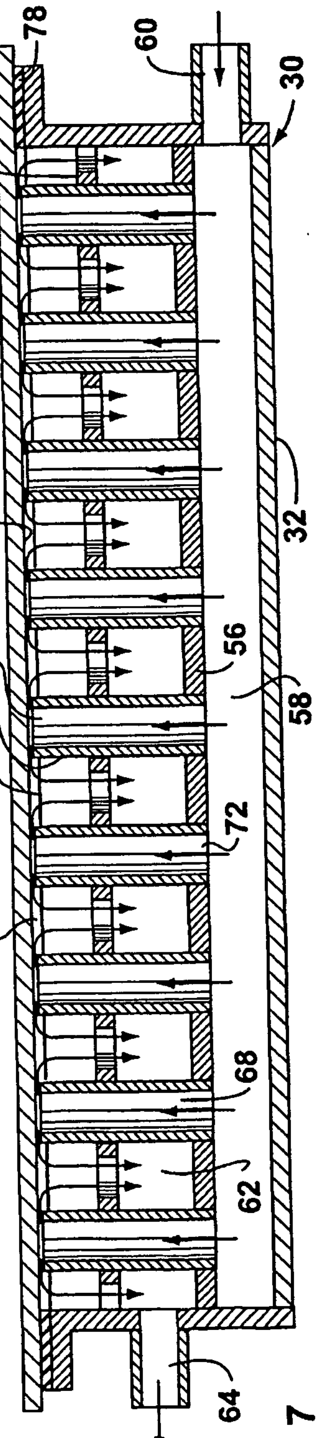
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FIG. 7